S P E C I F I C A T I O N

A METHOD AND APPARATUS FOR CHANGING THE OPTICAL INTENSITY OF AN OPTICAL SIGNAL USING A MOVABLE LIGHT TRANSMISSIVE STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a continuation-in-part and claims priority of the following related patent applications: (1) provisional U.S. Patent Application Serial No. 60/233,672 by Ying Wen Hsu, filed on September 19, 2000 and titled "Method For Switching Optical Signals Using Microstructures;" (2) provisional U.S. Patent Application Serial No. 60/241,762 by Ying Wen Hsu, filed on October 20, 2000, titled "Method for switching optical signals using microstructures;" (3) U.S. Patent Application Serial No. 09/837,829 (docket 263/176) by Ying Wen Hsu, filed on April 17, 2001 and titled "Optical Switching Element Having Movable Optically Transmissive Microstructure;" (4) U.S. Patent Application Serial No. 09/837,817 (docket 263/214) by Ying Wen Hsu, filed on April 17, 2001 and titled "Optical Switching System That Uses Movable Microstructures To Switch Optical Signals In Three Dimensions," all patent applications of which are expressly incorporated herein by reference for all purposes.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The field of the invention is devices that change the optical intensity of an optical signal and in particular, devices that use a movable light transmissive structure to change the optical intensity of an optical signal.

Background

[0003] There is a class of devices generally referred to as Variable Optical Attenuators (VOAs). A VOA is used to reduce the power of an optical signal so that the resulting power level is within the acceptable range of those devices or instruments working downstream from the VOA. For example, a VOA may be used to equalize the power levels of multiple optical signals before the signals are combined in a DWDM system (Dense Wavelength Division Multiplexing) for high-speed transport. This equalization is required because the multiplexed optical signals will be amplified before being transported and any excessively high power signals could be lost due to saturation. VOAs may also be required after the signals are multiplexed in a DWDM system to reduce the output power. The reason is that the actual power is dependent on the number of active channels, which can vary over time.

[0004] A VOA is one of the key components used in fiber optic communication systems. During the past decade, the demand for higher bandwidth driven by the Internet has resulted in a need for mass-producible and low cost optical components. A successful strategy used to reduce cost is to design optical components by leveraging the well-established manufacturing processes taken from the semiconductor industry. A

strong interest exists, therefore, to produce VOAs and other optical components from typical semiconductor materials such as silicon, silica, nitrite and others. New developments are also seeking to produce these components using active materials such as gallium arsenide because these materials can be used to produce light generating components. An ultimate goal is to integrate a maximum number of functions on a single substrate to minimize the manufacturing cost.

[0005] There are prior art methods for adjusting the output power of an optical signal. The most common way to adjust the power of an optical signal is by simply limiting the amount of light transmitted from one fiber to another fiber. This can be accomplished by inserting an object (optically opaque in the wavelength of interest) between the light-carrying fiber and the outgoing fiber. The optically opaque object, usually referred to as a shutter, can be moved in small distances such that the amount of light captured by the receiving fiber can be controlled precisely. Conventional VOAs move the shutter by using precise mechanical stages and motors that have resulted in large and expensive systems. Other techniques rely on optical properties of selective materials such as liquid crystals to affect the amount of light passing through the material. Electro-optics and thermo-optical effects have also been used to affect the amount of light transmitted.

[0006] More recently, it has been desirable to produce VOAs using materials and processes compatible with semiconductor manufacturing processes. FIG. 1 illustrates an example of a prior art approach where a miniature actuator 10 is fabricated directly on the silicon substrate 20. Light is conducted into the switching region by an optical fiber 22.

A shutter 24 is positioned between the end of the input fiber 22 and the entrance of the output fiber 26. The shutter 24 is supported by an actuator/micro-mechanism 10 produced out of silicon. The actuator/micro-mechanism 10 moves the shutter in the direction indicated by the actuation arrow. Electrical interface pads 28 may be coupled to the actuator/micro-mechanism 10 in order to control the actuator/micro-mechanism 10. By moving the shutter 24, more or less of the light from the input optical fiber 22 can be allowed to pass into the output optical fiber 26. This approach is described in U.S. Patent No. 6,173,105. A wide range of fabrication technologies referred to as MEMS processes (Micro-Electro Mechanical Systems) have been employed successfully to produce these micro-mechanisms. Different methods of actuation are available including electrostatic, thermal and magnetic. The use of MEMS technology allows precise control of the actuator/mechanism 10 as well as batch manufacturing processes.

[0007] One problem associated with a VOA based on the shutter approach is the difficulty of integrating it with optical systems that use waveguides. Waveguides, by contrast with shutters, are optically transmissive structures. In the typical semiconductor process, different layers of materials are sequentially deposited and patterned. In the shutter approach, the silicon shutter must be located on the same plane as the waveguides and also must be physically larger than the waveguides to provide effective blocking of light. These two requirements make it difficult to produce both shutter and waveguides in the same processing sequence. Although it is possible create the shutter and waveguides separately by breaking up the process and by selective masking, this approach increases potential misalignments and manufacturing complexity.

[0008] Ideally, a VOA design for integration with a waveguide-based system uses the same processing steps as that used to make waveguides. One choice is to introduce a mechanism into the waveguide that would modulate light. That can be achieved by introducing electro-optical, thermal, or acousto-optical effects into the waveguides. These methods, however, are limited to waveguides made out of certain active materials, which waveguides are generally difficult to manufacture. Another possibility is to use a waveguide with a movable section which acts as a shutter by doping the movable section of the waveguide so as to become opaque. However, all of these methods require significant deviations from standard waveguide manufacturing processes. Therefore, there is a need for a device that changes the optical intensity of an optical signal which uses standard waveguide manufacturing processes. There is also a need for a cost effective method of fabricating such a device.

Summary of the Invention

[0009] Generally, the device changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform.

[0010] Other systems, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts throughout the different views. However, like parts do not always have like reference numerals. Moreover, all illustrations are intended to convey concepts, where relative sizes, shapes and other detailed attributes may be illustrated schematically rather than literally or precisely.

[0012] FIG. 1 is a schematic illustration of a prior art variable attenuator which has a shutter.

[0013] FIGs. 2A and 2B are schematic illustrations of an example embodiment of a device that changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform, where FIG. 2A illustrates the movable platform in a first position and FIG. 2B illustrates the movable platform in a second position.

[0014] FIG. 3 is a schematic illustration of another example embodiment of a device that changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform, where the movable platform rotates.

[0015] FIG. 4 is a schematic illustration of yet another example embodiment of a device that changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform, where the movable platform is curved and has a prism coupler.

[0016] FIG. 5 is a schematic illustration of an example embodiment of a device that changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform, which illustration includes structures associated with the moving platform.

[0017] FIG. 6 is a schematic graph of the light output versus the offset in microns.

[0018] FIG. 7 is a schematic cross-sectional view of a movable waveguide having an air gap.

[0019] FIG. 8 is a schematic cross-sectional view of a stationary waveguide resting on an oxide layer of a substrate.

[0020] FIG. 9 is a schematic illustration of an example embodiment of a 4 x 4 optical switch coupled to VOAs.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] The improved device for changing the optical intensity of an optical signal uses a light transmissive structure, preferably a movable waveguide, whose position determines the amount of free space through which the optical signal must travel, thereby variably attenuating light. The phrase "light transmissive structure" includes structures that are optically transmissive such as waveguides and optical fibers, but not air gaps, mirrors and shutters.

[0022] FIGs. 2A and 2B are illustrations of an example embodiment of a device 30 that changes the optical intensity of an optical signal by using a light transmissive structure such as a waveguide disposed on a movable platform, where FIG. 2A illustrates

the movable platform in a first position and FIG. 2B illustrates the movable platform in a second position. Two stationary waveguides 32, 34 are positioned adjacent to the input and output of a movable waveguide 36. When the movable waveguide 36 is aligned with the stationary wavguides 32, 34 as shown in FIG. 2A, light from the source 38 is guided across through the movable waveguide 36. When the movable waveguide 36 is moved completely away from the stationary waveguides 32, 34, as in FIG. 2B, the input light has to traverse across free space 40. By setting the distance of the free space between the fixed waveguides 32, 34 such that a minimal amount of light is captured in the output fixed waveguide 34, significant optical attenuation can be achieved (e.g., up to 100% attenuation). To adjust the amount of light transmitted, the movable waveguide 36 is inserted into the light path to allow for the desired amount of light to pass through (e.g., up to 100% transmission). The movable waveguide 36 essentially acts as a variable conduit bridging the two junctions. Thus, the improved device 30 uses free space as a means of attenuating light and a movable waveguide 36 to variable adjust the amount of light passing from the input waveguide 32 to the output waveguide 34.

[0023] FIG. 3 illustrates another example embodiment of a device for attenuating light by moving a waveguide 50 relative to stationary waveguides 52, 54. FIG. 3 attenuates light by rotating the movable waveguide 50 so that less or no light is transmitted from the input waveguide 52 into the movable waveguide 50. In this example, less or no light is transmitted also from the movable waveguide 50 into output waveguide 54. A maximum amount of light is transmitted when the movable waveguide 50 is aligned with the stationary waveguides 52, 54. When the movable waveguide 50 is

rotated such that the entry surface of the movable waveguide 50 is blocked from receiving light from the input stationary waveguide 52, the transmission of light is completely terminated. Rotating the movable waveguide 50 to an intermediate position makes it possible for a portion of the light to be transmitted.

[0024] FIG. 4 illustrates yet another example embodiment of a device for using a movable waveguide 60 to attenuate light. In this example, light is attenuated by the air gap 62 between the stationary input waveguide 64 and the movable waveguide 60. This approach requires relatively larger movement (several millimeters) to translate the movable waveguide 60 in order to completely attenuate light. To couple light laterally into the stationary output waveguide 66, a prism coupler 68 will be required. The use of prism coupler 68 is well known to those skilled in the art of waveguide designs. In an alternative embodiment to FIGs. 3 or 4, other light transmissive structures may be used in place of one or more of the waveguides.

[0025] FIG. 5 illustrates a VOA device which uses a movable waveguide 70 and is fabricated with a MEMS micromachining manufacturing process. The device includes a waveguide 70 integrated on top of a movable platform 72. The movable platform 72 is supported on springs 74, which are connected to anchors 76 tied to the substrate. The movable platform 72, springs 74 and anchors 76 are all preferably produced from the same layer of material. To enable the platform 72 to move, an air gap (not illustrated) underneath the platform 72 is used so that the platform 72 is supported completely on the springs 74. There are several methods of producing a structure which is capable of being freely suspended; these methods are well known to those skill in the art of

micromachining. Materials such as silicon, silica, nitrite and metals have all been made successfully into freely-suspended micro-structures. Any appropriate material may be used in the VOA device.

[0026] To move the platform 72, actuators 80 are connected to the platform 72. A widely used actuator is the inter-digitated structure referred to as "comb fingers" because of their resemblance to combs. Preferably, the actuators 80 of the VOA uses inter-digitated structures. Such inter-digitated structures can be easily produced on the same layer as the platform 72. A set of comb fingers 84 is patterned onto the movable platform 72, while an opposing set 82 is patterned and fixed to the substrate. To actuate the actuators 80, an electrical voltage differential is applied to the fixed electrode 82 and the movable electrode 84. The resulting voltage differential generates an electrostatic attraction force and pulls the movable platform 72 toward the fixed electrode 82. Other actuation techniques could also be used. Examples include actuators whose operation is based on thermal, magnetic and/or piezo-electric drives. The design of actuators is well known to those skilled in the art of designing micromachined structures.

[0027] The movable platform 72 supports a waveguide 70 that bridges two adjacent and stationary waveguides 86, 88. By applying a varying level of electrical voltage to the actuator 80, the movable waveguide 70 can be moved by any desired amount. For precise movements, the comb fingers of the actuator 80 can be connected to a position sensing circuit, which preferably is coupled to movable and fixed sensing comb fingers 90, also referred to as position sensing electrodes. The change in the relative position between movable and fixed sensing comb fingers 90 generates a change

in the electrical capacitance between the fingers; this change can be detected and converted into electrical voltages through proper detection circuits. Commercial capacitance-to-voltage conversion chips are available. The position signal could also be used in a closed-loop control circuit to hold the movable waveguide 70 in a fixed position. The use of position circuits and control algorithms are well known to those skilled in the art of micromachine control. Other means of sensing such as those based on piezo-resistive, magnetic and/or optical methods are also viable.

[0028] Referring to FIG. 5, an optical signal is connected to the input waveguide 86, which preferably is mounted on a stationary platform which aligns the input waveguide 86 with the movable waveguide 70. On command from the system to attenuate power, an electrical voltage is send to the actuator 80 to move the movable waveguide 70. The actual power of light transmitted can be monitored from the output waveguide 88, which preferably is mounted on a stationary platform which aligns the outut waveguide 88 with the movable waveguide 70. Electrical power is applied to the actuator 80 until the desired attenuation is achieved. To lock onto the desired attenuation, the position of the movable waveguide 70 is "fixed" by monitoring the output voltage of the position sensing electrodes 90 or the power optical signal. Buffering or cladding 92 for the waveguides may be used as well.

[0029] FIG. 6 is a graph of the monitored output light power on the Y axis and the offset in microns on the X axis for a simulated design of a movable waveguide having the following dimensions: 6 micron width, 6 micron height, and 2 mm long. The transmitted power is slightly less than 100% due to loss across the air gap. This loss can

be reduced by using an index matching gel or by coating the face of the waveguides with anti-reflection film. As the movable waveguide 70 is moved, light is attenuated until approximately 10 microns of movement. The resulting attenuation for the given geometry is about –27 dB. Higher attenuation is also achievable with further optimization.

[0030] FIGs. 7 and 8 illustrate cross sectional views of a movable and a stationary waveguide. FIG. 7 shows a suspended waveguide 100, while FIG. 8 shows a stationary waveguide 102 positioned on top of the substrate 104. The movable waveguide 100 is suspended over an air gap 106 over the substrate 104. The movable waveguide 100 preferably includes a core 108 surrounded at least partially by a cladding 110 and a buffer 112. The buffer 112 rests on a silicon layer 114. Turning to FIG. 8, the stationary waveguide 102 preferably includes a core 108 surrounded at least partially by a cladding 110 and a buffer 112. The buffer 112 rests on a silicon layer 114, which in turn rests on an oxide layer 116 on the substrate 104.

[0031] FIG. 9 illustrates an example of integrating the improved device with an optical switch. For switches with a smaller number of ports, the range of the output power will be small, but for switches having a large number of ports, the range of output power can vary significantly due to the greater number of different paths which can be taken by each optical signal. A large range in the switch output would be undesirable and will require using VOAs to equalize the output. For such an optical switch, the use of any of the improved devices described in this patent specification will greatly simplify the integration of a VOA and the optical switch using the same manufacturing process.

For example, input optical fibers 120 are coupled to a 4 x 4 optical switch 122. The 4 x 4 optical switch 122 is coupled to VOAs 124, each VOA being one of the improved devices described herein. The 4 x 4 optical switch 122 and VOAs 124 are mounted to a common substrate 126. Because there are 4 output ports in this example, there are 4 VOAs 124. Each of the four VOAs 124 is coupled to an output optical fiber 130. Each VOA 124 may be separately controlled to attenuate the light as desired.

[0032] While various embodiments of the application have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of the subject invention. For example, each feature of one embodiment can be mixed and matched with other features shown in other embodiments. Features and processes known to those of ordinary skill in the art of optics and semiconductor processing may similarly be incorporated as desired. Additionally and obviously, features may be added or subtracted as desired. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.